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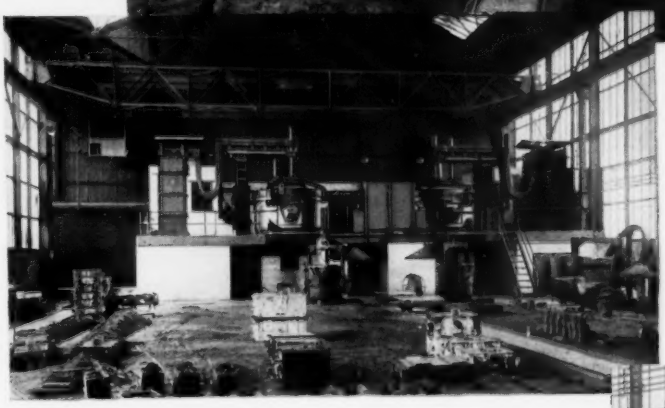

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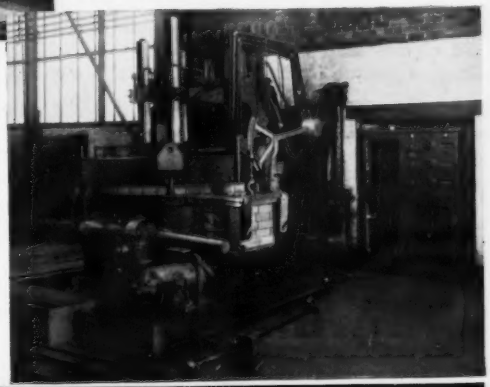

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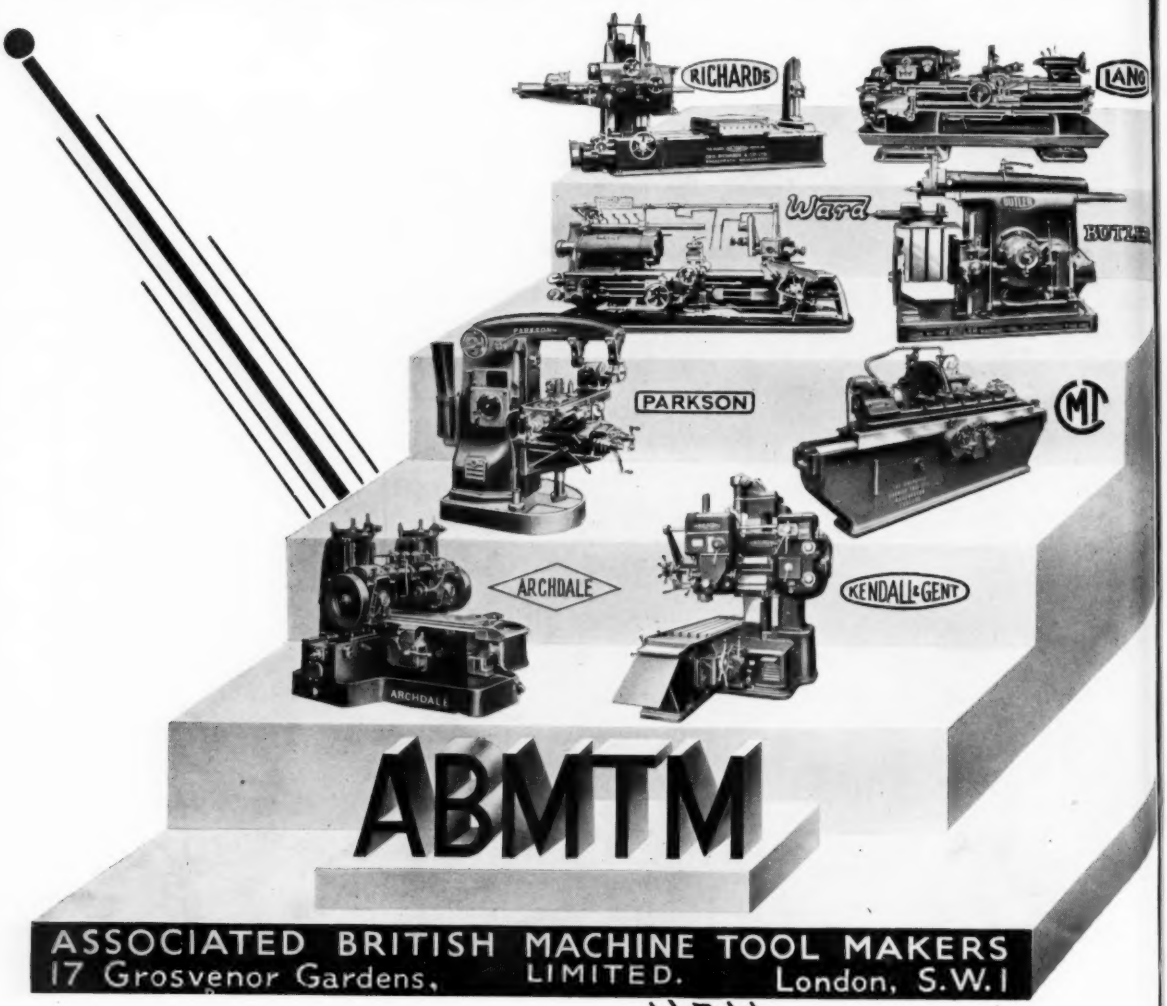

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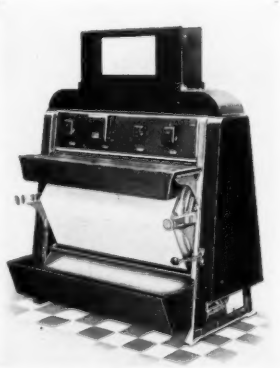

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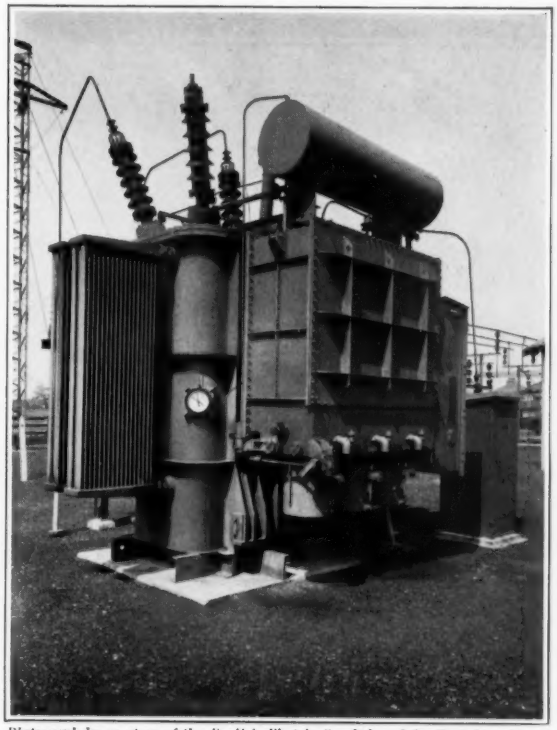

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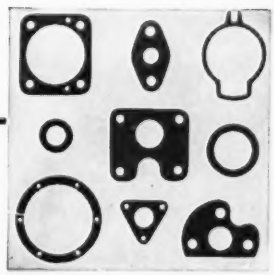

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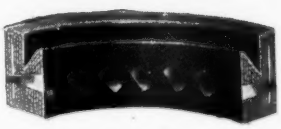

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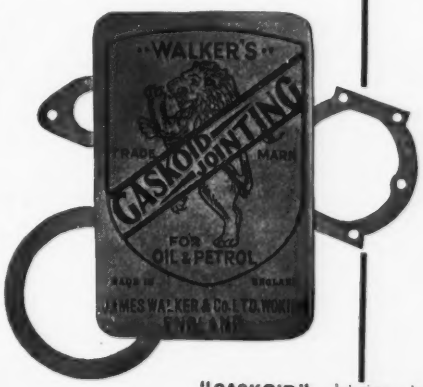

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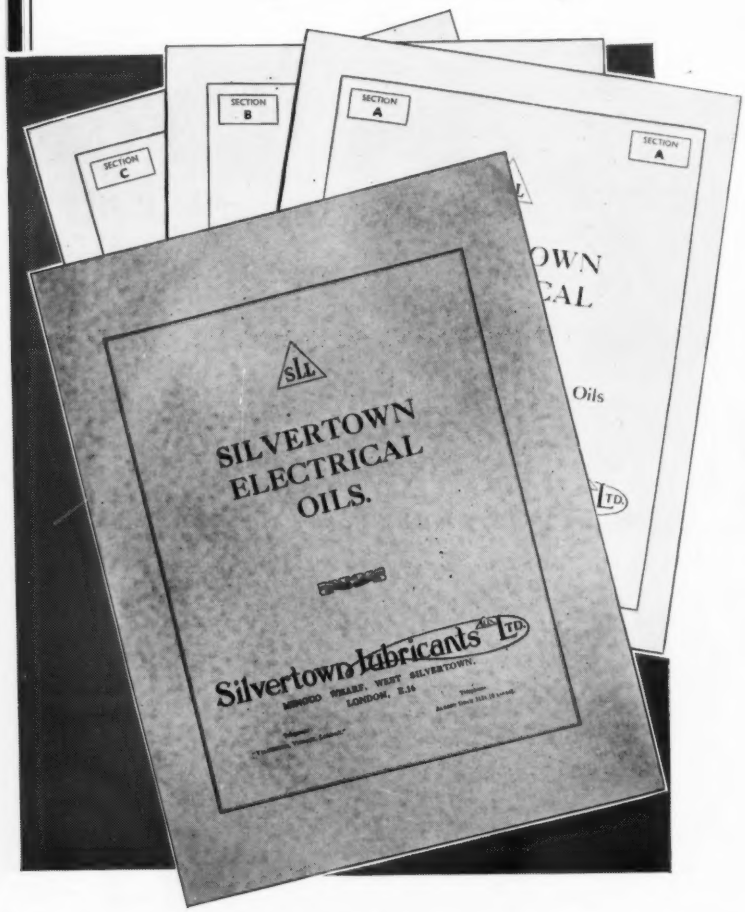

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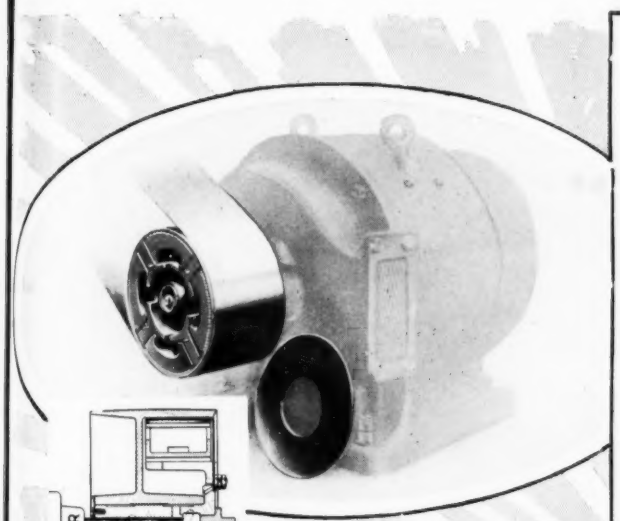

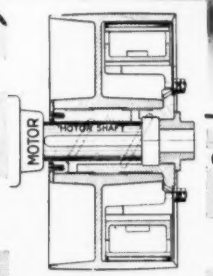

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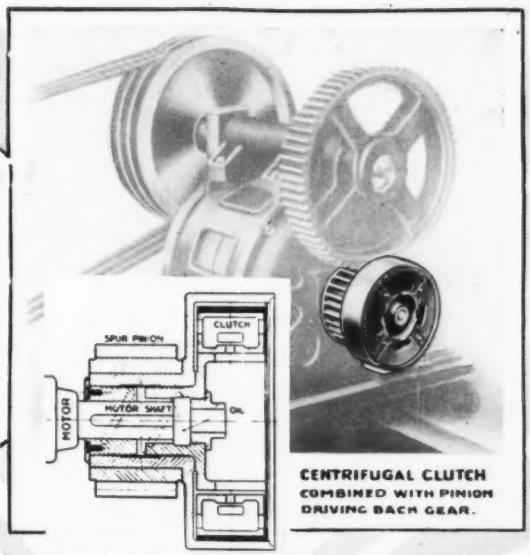

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All Communications respecting Editorial Contents should be addressed to THE EDITOR, THE ENGLISH ELECTRIC JOURNAL, THE ENGLISH ELECTRIC COMPANY LIMITED, STAFFORD.

EDITORIAL.

The first article in this issue, " Steam Turbines Past and Present," commences with a review of the earliest known types of turbines. An interesting fact given is that the two fundamental principles on which the modern steam turbine operates, namely, reaction and impulse, were known many hundreds of years ago, being used respectively by Hero in his turbine of 120 B.C. and by Branca in his turbine designed in 1629.

After a reference to early nineteenth century turbines, the article continues with brief descriptions of the turbines developed towards the latter end of that century by de Laval, Parsons, Curtis and others, which were the first turbines to have any commercial application. After mention of some of the early turbines made by Messrs. Willans & Robinson (now incorporated in The English Electric Company) the article concludes with a brief review of a few of the 3,000 r.p.m.

units made by The English Electric Company, who have been pioneers in the development of turbines of large outputs operating at this speed.

" Watthourmeter Bearings," by Mr. G. Tilstone, is the title of the second article. It is perhaps not generally appreciated that the watthourmeter lower bearing is the most highly stressed bearing known to engineering. The Author reviews the fundamental duty of the lower bearing and discusses the respective features of the ball and the pivot type bearing meters. An interesting description is also given of the manufacture of the components of the " ball bearing " which the Company have adopted as the standard for the " English Electric " range of meters.

Power Factor improvement is a problem which on occasion confronts most industrial users of electricity. The concluding article deals with the Methods and Economics of Power Factor Improvement. The Company manufacture a wide range of machines for power factor correction purposes and a number of these are described and illustrated.

Some interesting examples are given of the financial savings that can be made on a works system by the installation of power factor correction machines. Methods of calculating the size of correcting apparatus are also dealt with.

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Steam Turbines Past and Present.*

In power station work where the fuel is coal, the steam turbine has become the recognised form of prime mover, as it can be built in sizes far beyond the capacity of any reciprocating engine. Furthermore, it can avail itself of the additional energy obtainable from the highest limits of pressure, temperature and vacuum, and its consumption, other than in very small sizes, is much lower than could be obtained by any steam engine. To-day there are in operation turbines capable of developing continuously over 200,000 kW.

The history of the steam turbine is contemporaneous with that of electrical machinery, for although the turbine has now established its position for many other purposes, its development has been fostered almost entirely by the demand for a prime mover suited to the characteristics of electric generators. In the early days of the electrical industry the dynamo had to be driven by a belt from the engine as the speed of the latter was too low to admit of direct coupling. When powers had to be transmitted for which belt driving was impracticable, so that direct coupling became essential, two alternatives were open, either to construct the generator of large diameter so that it could generate efficiently when rotating at the same speed as the slow speed engine, or to devise a type of engine which would run at a higher speed. A certain amount of progress was made along the former lines and some units of considerable size were built, but their cost was excessive and a better line of development was that inaugurated by Peter Willans, who invented a totally-enclosed single-acting engine which could be run at a speed much nearer that desired by the dynamo designers.

With the demand for generating units of greater capacity, the limitation of any type of reciprocating engine became apparent, and as a result the steam turbine as a practicable type of prime mover was introduced by the Hon. Charles Parsons and Gustaf de Laval. The work of these two great pioneers of the turbine industry was started in about 1883-4, so that generally it may be said that the development of the steam turbine has taken something over fifty years.

Although the output of the early machines was a matter of only a few kilowatts, a new era of progress had been inaugurated, and electrical engineers were now provided with a means of obtaining any power they might demand at a speed as high as ever they could utilise efficiently.

Fig. 1.—Model of Hero's Turbine, about B.C. 120.

* *Based on a paper "The History of the Steam Turbine" by J. P. Chittenden and J. T. Moore, read before Informal Meetings of the I.E.E. at Leeds and Dundee, December, 1937, and January, 1938.*

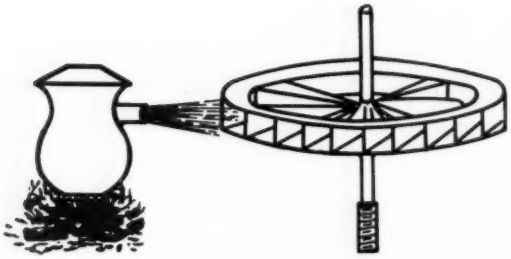

Fig. 2.—Sketch of Giovanni Branca's Turbine, 1629 A.D.

Fortunately for electrical practice, the relationship between efficient turbine speeds and alternator speeds is a suitable one, so that no difficulty arises in the greatest field of power generation, and as outputs of alternators increase, so can turbines be designed suitable for driving them in a highly efficient and reliable manner.

The steam turbine is actually of ancient origin, having been known about 2,000 years ago. The first turbine was made by Egyptian priests in about the year 120 B.C., and is described by Hero of Alexandria in his treatise on "Pneumatics." It consisted, as will be seen from Fig. 1, of a hollow ball mounted on its axis between two pivots, one of which, being hollow, served as a steam pipe from the boiler below, and which supported the ball as illustrated. The ball was provided with two bent tubes, arranged diametrically opposite and in a plane at right angles to the line of the pivots. The steam issuing from the tubes set up an unbalanced pressure, or reaction, and so caused the ball to rotate on its pivots. This, the first known turbine, is an excellent example of the principle of reaction which, in a modified form, is used to-day in many turbines.

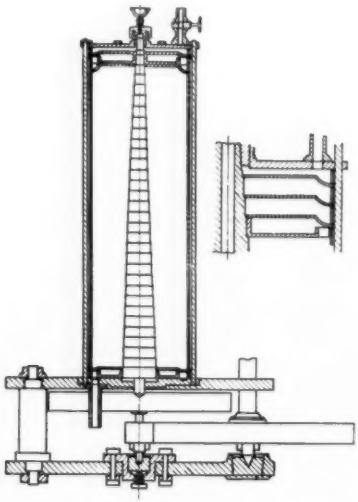

Fig. 3.—Real and Picon's proposal for a multi-stage impulse type Turbine, 1827.

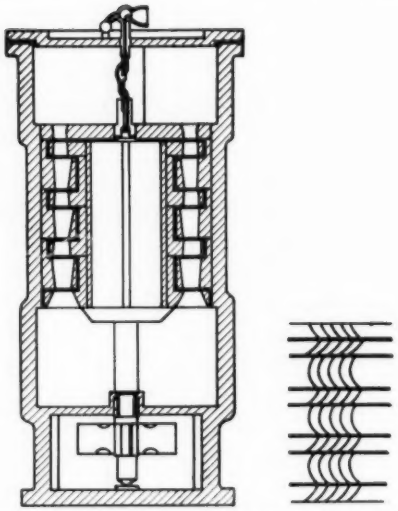

Fig. 4.—Tournaire's proposal for a multi-stage reaction type Turbine, 1853.

From 120 B.C. there is no further recorded information about the development of the steam turbine until the year 1629, when Branca introduced what was probably the first impulse turbine, and the first direct application of the impulse principle. His apparatus is shown in Fig. 2 and consisted simply of a vessel of boiling water, with the issuing steam directed as a jet on to a wheel containing vanes round the periphery. The velocity of the jet impinging on the vanes caused the wheel to revolve on exactly the same principle as the present-day impulse turbine.

Naturally in both Hero's and Branca's turbines the efficiency was exceedingly low, but they are of great interest as illustrating the two fundamental principles on which steam turbines operate.

During the century following the introduction of Branca's turbine, little is known about the development of the turbine. It had been receiving the attention of several investigators, however, as the principle of using a number of stages to improve the efficiency was referred to by James Sadler in 1791, and in 1827 Real and Picon built a multi-stage turbine of the impluse type. This machine is shown in Fig. 3. It was evidently recognised that to obtain a good efficiency it was necessary either to run the turbine blades at a very high speed with one or few stages, or alternatively, to use many stages and run the blades at a more moderate speed.

That the above principle was fully appreciated by the middle of the nineteenth century is clear from the description of the multi-stage reaction turbine which Tournaire evolved in 1853. His turbine is shown in Fig. 4 and he made it clear that its operation was chiefly dependent on the difference in pressure between the inlet and outlet of the blades, using the moving blades as nozzles for the expanding of the steam on the reaction principle.

From about 1870, various designs of multi-stage turbines were put forward, notably Hansen's in 1870, of the axial flow reaction type, and Cutler's in 1879, of the radial flow reaction type, but there appears to have been no industrial application of any of these early turbines. It remained for de Laval in 1883 to make the first practical application of the impulse turbine, after more than five years' experimental work, when he applied the turbine to the drive of his milk separator.

In the first turbine of de Laval, the nozzles were of the simplest form, but about 1888 de Laval evolved his expanding nozzle, and flexible turbine wheel shaft. This was a very great advance on all previous impulse turbines, in that the convergent-divergent nozzle, as it is known to-day, enabled the steam to be expanded completely in the one stage of nozzles, and the use of the flexible shaft enabled a suitably high peripheral speed to be obtained with safety.

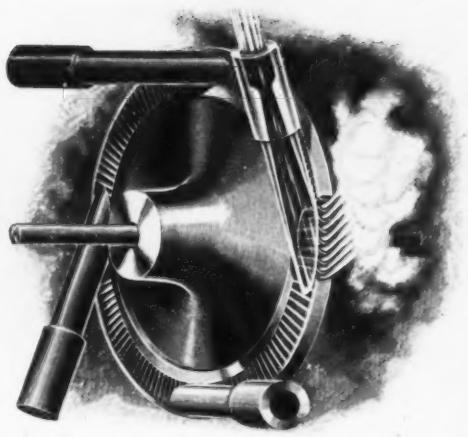

Fig. 5.—Pictorial sketch of the de Laval turbine wheel.

In 1893, the de Laval Steam Turbine Company was formed to exploit the single-wheel impulse turbine, and a pictorial illustration of this type of turbine is shown in Fig. 5. This shows clearly the two main features of the de Laval turbine, the flexible shaft and the convergent-divergent nozzles. De Laval undoubtedly realised the

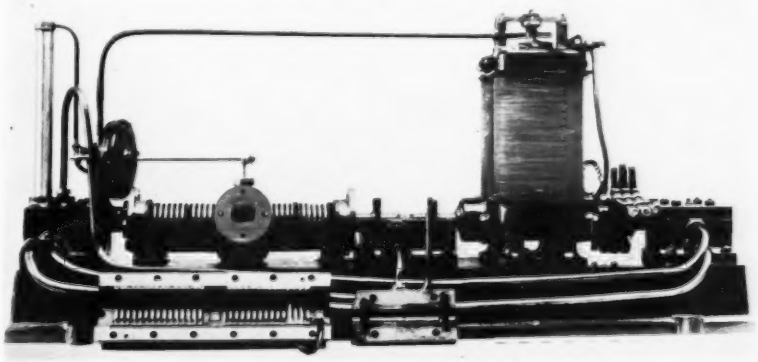

Fig. 6.—The first Parsons turbine (top cover removed) and generator which it drove, 1884.

importance of the fundamental law that, in order to obtain a high efficiency, the speed of the blades should be nearly half that of the steam jet from the nozzle, and as that naturally involved very high blade speeds of the order of 1,000 to 1,200 feet per second, his flexible shaft was an ingenious solution of a difficult problem.

Following the commercial introduction of the de Laval turbine in 1883, Sir Charles Parsons, after many experiments, manufactured in 1884 his first multi-stage reaction turbine, this turbine being the first successful practical application of the reaction principle. A photograph of the original turbine, with the generator which it drove, is shown in Fig. 6.

The first turbine of Parsons, although a multi-stage machine, ran at the very high speed of 18,000 r.p.m., but in later turbines, the speed was reduced by the introduction of more stages and greater peripheral speeds, leading gradually to the single rotation reaction turbine as known to-day.

It is interesting to note in passing, however, that Sir Charles Parsons realised as early as 1902 the advantages of the double rotation turbine. Robert Wilson, of Glasgow, also had experimented with the double rotation turbine, as well as Siemens Schuckert on the Continent, but it remained for Ljungstrom in 1908 to resuscitate the double rotation radial flow turbine and produce a machine of this type in practical form.

While Parsons was developing his reaction turbine for use as a prime mover for the drive of electrical generating machines he soon realised the great suitability of the turbine for the drive of a ship's propeller, and much development work was carried out in this sphere. A particularly interesting illustration in this connection is shown in Fig. 7, which is a view of the experimental ship "Turbinia," taken at Portsmouth at the Diamond Jubilee in 1897. This was the first successful application of the steam turbine to marine propulsion and at the time the results obtained were far in advance of anything previously achieved by ships fitted with reciprocating engines.

In the years immediately following the introduction of the de Laval single-wheel impulse turbine, the inherently high speed, which was a disadvantage in many cases when it was desired to avoid the use of speed reduction gearing, led investigators to explore again the possibilities of the multi-stage impulse turbine. Professor Rateau produced, in 1896, his design of multi-stage impulse turbine, and to him must probably be accorded the distinction of being the first to apply commercially the multi-stage impulse turbine incorporating all single impulse stages. In the same year, however, Curtis, in America, evolved his multi-stage impulse turbine incorporating velocity compounded stages, so that from 1896 began the development of the multi-stage impulse turbine to its modern form.

From about 1896 de Laval also was experimenting with the multi-stage impulse turbine, and before the end of the nineteenth century, multi-

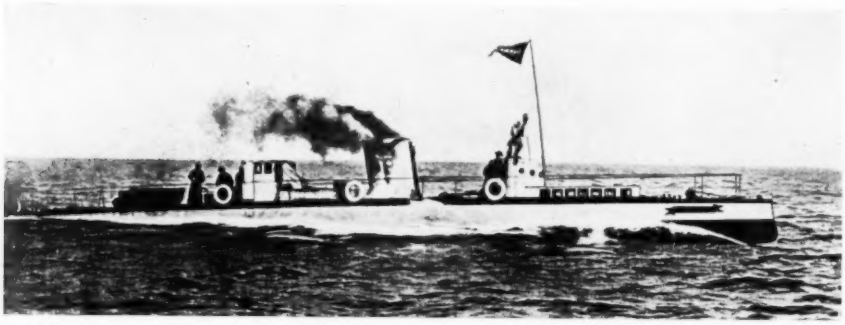

Fig. 7.—The experimental ship "Turbinia," at Portsmouth, 1897.

stage impulse designs were being produced by de Laval in Sweden, Rateau in France, and Curtis in America, while the multi-stage reaction turbines by Parsons in this country were very far advanced. Parsons, de Laval, and Rateau, and Curtis in the early stages, all favoured the horizontal turbine, but within a few years the Curtis turbine was being developed also as a vertical machine.

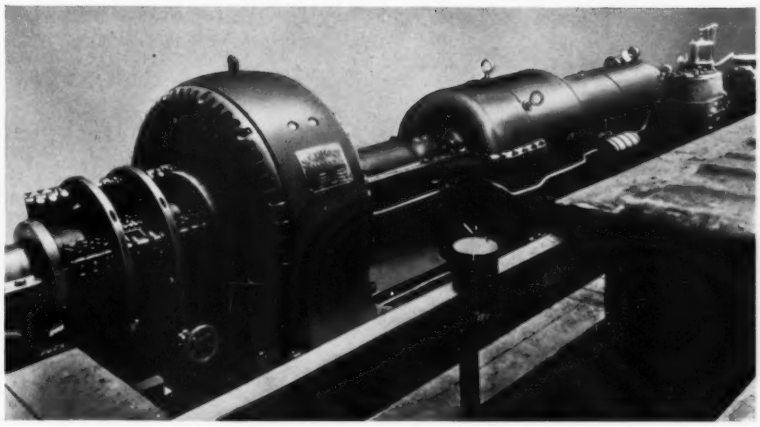

Fig. 8.—1,000 kW., 1,500 r.p.m. "Willans & Robinson" Turbine installed at Linwood Mills, Paisley, 1904.

By 1900 interest in the steam turbine as a prime mover was widespread, and within the next few years many concerns had taken up the manufacture of turbines, the principal field of application being for the drive of electric generators. Messrs. Willans & Robinson, Rugby (now incorporated in The English Electric Company) took up the manufacture of the reaction turbine in 1904, and a number of machines of this type were constructed by them, but later, for the first stage of the turbine, an impulse wheel was adopted. Fig. 8 shows the first turbine made by this firm and supplied in 1904 to the Linwood Paper Mills, Paisley. It was a 1,000 kW. machine running at 1,500 r.p.m. and driving a D.C. generator direct.

Within the next few years other firms took up the manufacture of both impulse and reaction steam turbines, and by 1910 the radial-flow double rotation turbine had been developed and put on a commercial basis by Ljungstrom in Sweden.

In America up to 1912 the vertical-shaft turbine was extremely popular, and units up to 20,000 kW. capacity were manufactured, but this appeared to be the limit of the design and with the horizontal turbine increasing in popularity, larger sizes made after this date were all of the horizontal type.

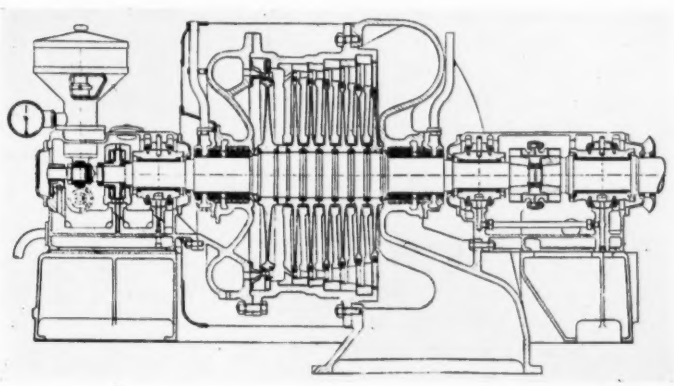

Fig. 9.—Early impulse type turbine with or without velocity compounded wheel.

In Great Britain there was little demand for large sizes prior to 1914, the most common ranging from 5,000 kW. to 10,000 kW., and there was a general tendency towards turbines running at a speed of 3,000 r.p.m., particularly for the smaller outputs. A section of a 5,000 kW. machine of this date is shown in Fig. 9 and a large number of this type were built by Messrs. Willans & Robinson during the War period. The design consisted of comparatively few impulse stages

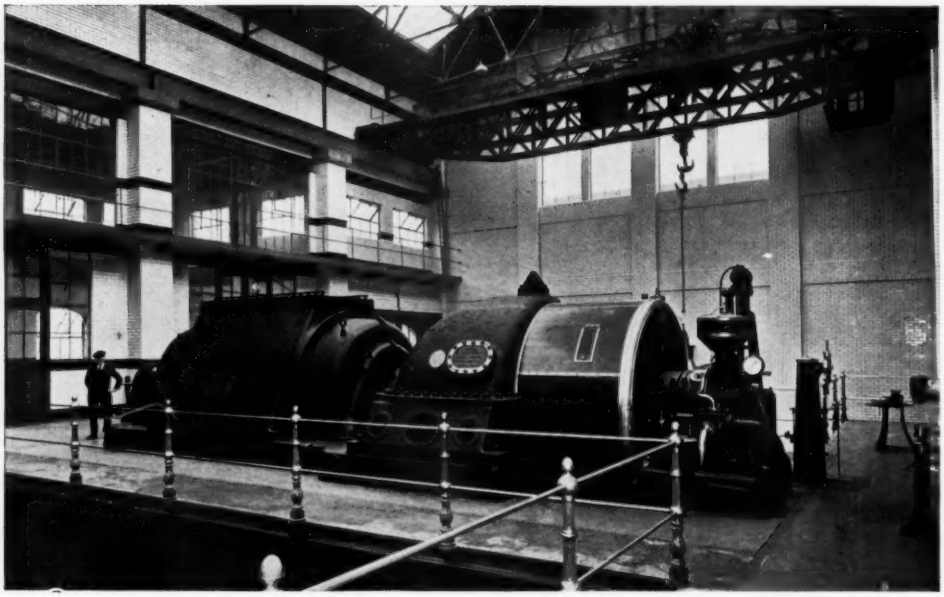

Fig. 10.—Single cylinder 15,625 kW., 3,000 r.p.m. multi-stage impulse turbine supplied to Bolton Corporation in 1923.

of moderate diameter, with or without a velocity compounded wheel in the first stage.

During the years of the Great War, development of the steam turbine was to a large extent at a standstill, but immediately following the conclusion of the War, keen competition gave a considerable fillip to development and the steady rise in individual outputs can be clearly traced from 1919-20.

As the demand for larger machines increased, a point was very soon reached where it was difficult to obtain the required high efficiencies with single-cylinder turbines, because no more stages could be accommodated on the single-span rotors without encountering troubles from many sources. This led to the introduction of multi-cylinder turbines for high efficiency units, although for medium outputs of the order of 10,000 to 15,000 kW., the single-cylinder turbine still remained popular. Fig. 10 shows a typical single-cylinder 15,000 kW., 3,000 r.p.m. " English Electric " multi-stage impusle turbine supplied to Bolton Corporation Electricity Department in 1923. This turbine at the time was one of the largest single-cylinder 3,000 r.p.m. turbines manufactured for installation in this country.

At the same time, however, many multi-cylinder turbines were being supplied in this country for outputs from as low as 10,000 kW. upwards, and Fig. 11 shows a section of a 20,000 kW., 3,000 r.p.m. two-cylinder turbine supplied by the Company to Bradford Corporation in 1925. This turbine, the forerunner of its type, is of particular interest as being the first two-cylinder impulse-reaction turbine built in this country, the high-pressure cylinder being of the impulse type throughout, while the low-pressure cylinder is of the outwards double-flow reaction type.

This design, retaining the same rotational speed of 3,000 r.p.m., has been extended up to sizes of 40,000 to 50,000 kW., and a sectional arrangement of the " English Electric " 30,000 kW., 3,000 r.p.m. turbine supplied in 1929 to West Ham Corporation is shown in Fig. 12. This illustrates the main features of the impulse high-pressure cylinder and the reaction low-pressure cylinder, the latter being of the inwards double-flow type with twin L.P. rotors, to obtain a unit

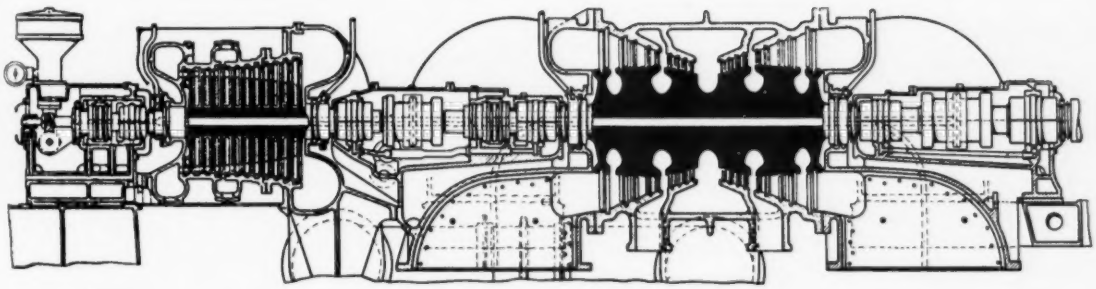

Fig. 11.—Sectional arrangement of a 20,000 kW., 3,000 r.p.m. two-cylinder " English Electric " turbine supplied to Bradford Corporation in 1925.

having a critical speed well above the running speed.

Two 40,000 kW., 3,000 r.p.m. turbines of similar design to that shown in Fig. 12, have been supplied this year by The English Electric Company for the Ferrybridge Power Station of the Yorkshire Electric Power Company and the curve in Fig. 13 will be of interest in illustrating the progress made by this Company since 1904 in the outputs of steam turbines designed to run at 3,000 r.p.m.

The intensive competition following the Great War was responsible for much experimental and research work in the realm of higher steam pressures and temperatures with a view to reducing fuel costs. Opinions naturally vary widely as to when it is an economic proposition to use high steam pressures and temperatures, but in principle the higher the steam pressure the greater is the minimum size of turbine which can be justified.

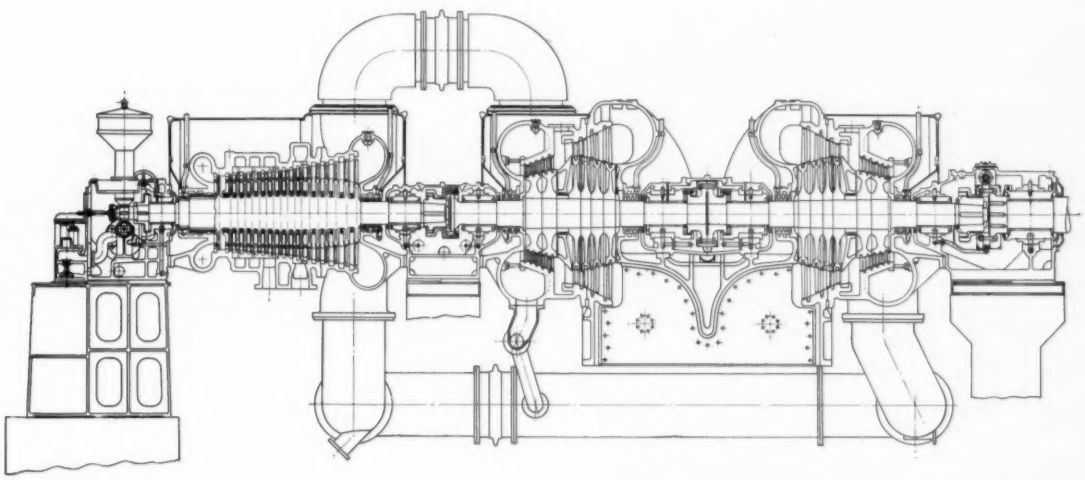

Fig. 12.—Sectional arrangement of an " English Electric " 30,000 kW., 3,000 r.p.m. turbine supplied to West Ham Corporation in 1929.

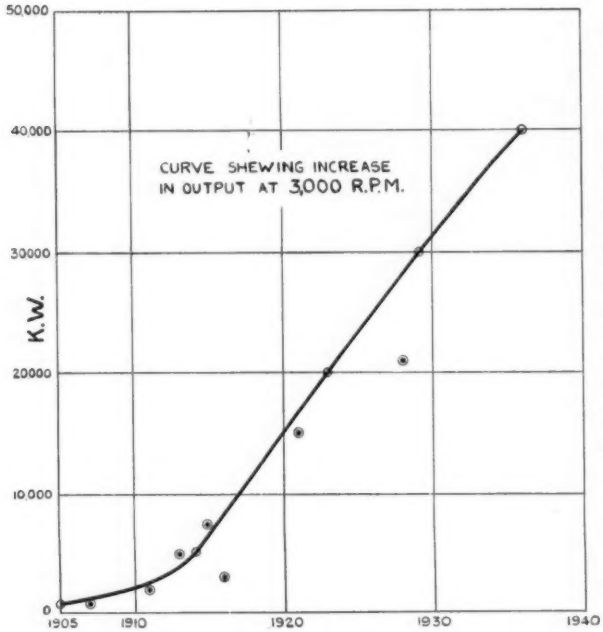

Fig. 13.—Curve showing increase in outputs (1905-1939) of "English Electric" turbines operating at 3,000 r.p.m.

was first applied at the Valley Road Power Station of Bradford Corporation in 1929.

The "superposed" unit was supplied by The English Electric Company, and a section through the turbine, designed to run at 6,000 r.p.m. driving the alternator through gearing, is shown in Fig. 14. The turbine is of the pure impulse type with the discs forged solid with the shaft, an arrangement now general for small high-speed impulse machines. The same arrangement is now general also for the impulse rotors in the H.P. cylinders of combined impulse-reaction two-cylinder machines of medium and large outputs at 3,000 r.p.m.

The "superposed" turbine has been very successful in the application of higher steam pressures and temperatures to existing normal plant, and in America where "superposing" has been widely adopted, there are many such turbines with outputs of 50,000 to 60,000 kW. in one unit.

The latter statement refers to units in which the steam is expanded right down to vacuum, but there are many special cases where high pressures and temperatures are justified with quite small machines, such as back-pressure turbines expanding steam at a high pressure into an existing lower pressure steam system for further use in low pressure turbines. This system, termed "superposing," has been much applied for improving the thermal efficiency of low pressure stations, and in this country the system, with a steam pressure in excess of 1,000 lbs./sq. in.,

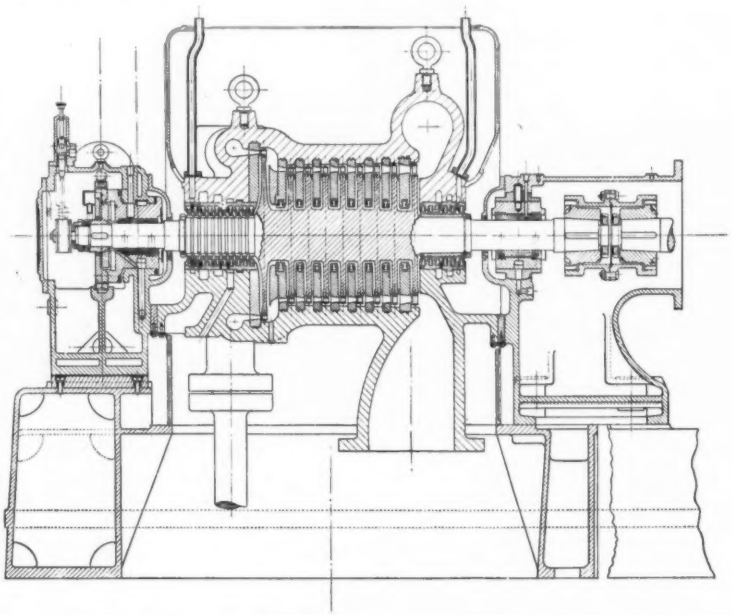

Fig. 14.—Sectional arrangement of a back-pressure turbine for high initial pressure and temperature, operating at 6,000 r.p.m.

For condensing turbines, pressures of 1,200 to 1,500 lbs./sq. in. are quite common in America and on the Continent, but in this country there are only a comparatively few plants operating with steam pressures much over 650 lbs./sq. in. Additional plants, however, are in course of manufacture in this country for pressures up to 1,900 lbs./sq. in., and the higher ranges of steam pressure will undoubtedly become more common in the future.

With pressures of the order of 1,200 to 1,500 lbs./sq. in., the limitation of the total temperature to 900 to 950 deg. F., a point to which further reference is made later, results in the steam at the exhaust end possessing a considerable degree of moisture. This comparatively high moisture content in the low pressure stages would have led in the past to appreciable wear of the blading in these stages, but the problem has been solved by the employment of special drainage arrangements and the fitting of hardened steel shields on the inlet edges of the last few rows of blading. The subject has recently been dealt with in detail in this Journal,* and typical photographs shown of blades after several years' service without shielding and after a similar period with shielding fitted.

The other problem associated with increased steam pressure which arises from the need to limit the wetness at the exhaust to reasonable proportions on the score of efficiency, is that of high total temperatures. Such temperatures, however, have now been made possible by the employment of steels containing a small percentage of molybdenum. From Fig. 15, it will be seen that as compared with a plain carbon steel, very much better creep properties are obtainable, with in consequence, a greater factor of safety. Even so, it will be noticed that the maximum permissible steam temperature to-day is limited to about 950 to 960 deg. F.

Steam pressures of the order of 1,900 lbs./sq. in., even with the temperature taken as high as possible, would result in excessive moisture

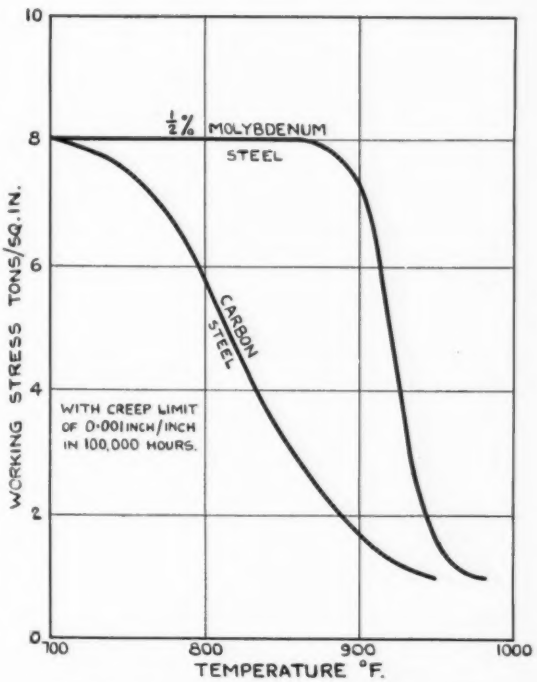

Fig. 15.—Curves showing the effect of temperature on the strength of steels.

in the low-pressure stages, and with such pressures it is usual to employ reheating of the steam at an intermediate stage of the turbine. Even with a pressure of 1,200 to 1,500 lbs./sq. in. reheating is sometimes employed, but there is not the same necessity as with pressures as high as 1,900 lbs./sq. in. or over.

From the foregoing brief survey of steam turbines past and present, some conception may be obtained of the great advances that have been made in output, speed, and efficiency during the last thirty years or more, and these improvements can be attributed in the main to the employment of a greater number of stages and higher peripheral speeds at the exhaust end, coupled with better materials, workmanship, and closer attention to detail.

Acknowledgments are made for permission for the reproduction of descriptive material and illustrations relating to the early types of steam turbines.

* *See L. C. Hookins, "Wetness in Steam Turbines," The English Electric Journal, July, 1938 (Vol. IX, No. 2), and March, 1939 (Vol. IX, No. 5).*

Watthourmeter Bearings.

By G. TILSTONE, A.M.I.E.E., Chief Engineer Meter Department.

In the early days of the development of the watthourmeter it became apparent that the lower bearing of the meter presented new problems, upon the satisfactory solution of which the success of the instrument would ultimately depend, and it was natural that meter inventors turned to the experience of designers and manufacturers of watches and clocks, who were pioneers in the use of precious stones as bearings.

The early meter designers must have obtained a great deal of assistance from a study of the then current horological practice, but it was soon realised that the conditions obtaining in the meter bearing were in many respects considerably more onerous than those met with in time pieces, particularly with regard to the weights of the parts to be supported whilst in rotation. The development of the alternating current meter added still further to bearing problems as the bearing was required to withstand the alternating current vibration inseparable from this type of meter.

O. B. Shallenberger, Chief Engineer of the Westinghouse Company in America, invented the original Shallenberger A.C. meter, which appeared on the market in its fully developed form in 1888 and marked a very definite step forward in the design of the alternating current meter, in that it provided a metering system commercially applicable. In common with the meters of the period, it employed a pivot and jewel at the lower end of a vertical rotor shaft. It is significant that the fundamental form of vertical shaft has remained, although it will be seen that the forms of bearings employed at the lower end ultimately became divided into two fairly distinct groups—the ball bearing and the pivot bearing.

In 1902 the Westinghouse Company of America introduced the bearing popularly known as the "Ball Bearing"; this was a radical departure from any of the contemporary designs. It consisted of a highly-polished steel ball placed between two cup sapphires, the upper sapphire rotating with the shaft and the lower one being held stationary in the lower bearing screw. This bearing has proved its superiority by its ability to stand up to extraordinary rough treatment and to give many years of trouble-free service.

The first meter incorporating this bearing was the "Westinghouse Round Type Wattmeter," which will be remembered by many meter engineers in this country, as having been in advance of most designs then available.

It is one of the outstanding facts in the history

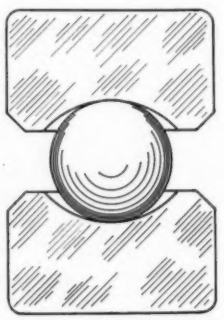

Fig. 1.—Components of Ball Bearing and Pivot Bearing.

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of meter development that the " Westinghouse Type Ball Bearing " has remained substantially unchanged for thirty-seven years and is still the only type of bearing employed by that Company.

During this period the number of different types of pivot bearings which have been produced, modified and superseded by new designs has been legion, but there is no evidence that any has exceeded the ball bearing in the length of trouble-free service obtainable.

The ball bearing is the standard bearing of the " English Electric " range of meters, although an approved pivot bearing meter is available where a preference is expressed for it.

It will be of interest to review briefly the fundamental duty of the lower bearing.

The bearing is required to support the rotor with as low an initial friction as possible and to continue to function satisfactorily with as small an increase in friction as possible over a period of many years without attention having to be given to it. The latter condition emphasises the vital necessity for freedom from disintegration of any of the bearing components under the high stresses imposed. It is generally accepted on the basis of calculation that the intensity of pressure in the average pivot meter is 50 tons per square inch, while in the ball bearing the intensity of pressure will be approximately half this amount.

The early designers were faced with a very formidable problem in devising bearings to support the very heavy rotors then found necessary, and a variety of new bearings appeared as a result of the work of inventors in Great Britain, the U.S.A., and in Europe.

Figs. 1a and 1b show to scale the essential parts of the ball bearing and those of the pivot bearing, whilst Figs. 2 and 3 show the corresponding assemblies. Figs. 1a and 1b will serve to illustrate several features of special interest. It will be noticed that the diameter of the ball is considerably greater than that of the pivot, the actual dimension being: Radius of ball, .03125 in., and radius of pivot .02 in.

The jewel in the pivot bearing is identical with one of those in the ball bearing, both having a radius of curvature of .0465 in.

It will be appreciated that although the areas of contact between the ball and its jewels are theoretically point contacts, the intensity of pressure applied either by normal running or in transit is considerably less than in the case in the pivot bearing, hence the risk of a damaged jewel from all causes is very much reduced, while the ball itself is almost indestructible.

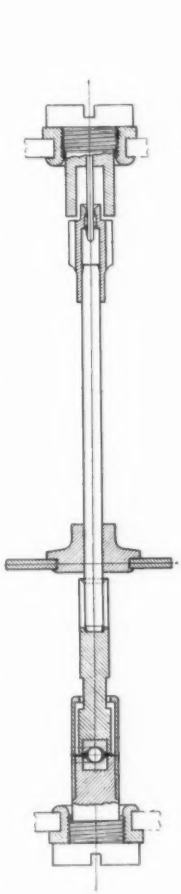


Fig. 2.—Assembly of Meter Shaft for Ball Bearing.

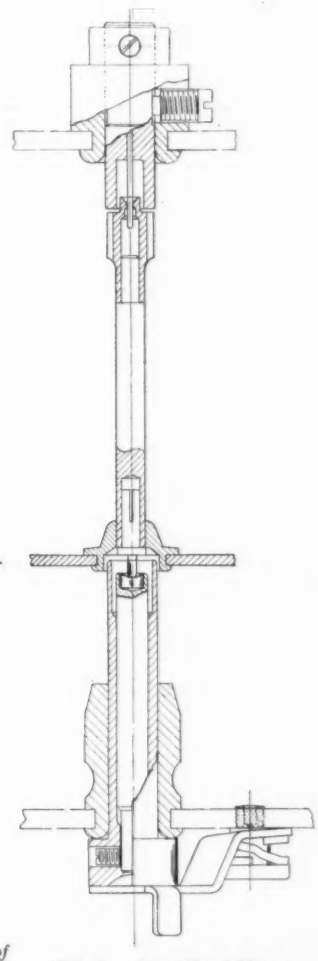


Fig. 3.—Assembly of Meter Shaft for Pivot Bearing.

In the case of the ball bearing there is no necessity to have the jewels spring-supported as is the case with many pivot-type meters, and the ball possesses a further advantage of being able to operate satisfactorily over a period of years without requiring lubrication. In the case of the pivot bearing, maximum and minimum permissible radii of the pivot are determined by a number of conflicting factors. The larger the diameter of the pivot the greater will be the friction ; the smaller the diameter of the pivot the smaller will be the friction ; but the stresses at the surface of the jewel will be increased with attendant possibilities of damage in transit, which will show as a rupture of the jewel face. The most minute damage to the jewel at the point of bearing contact will lead ultimately to the complete failure of the bearing.

From the safety aspect the average diameter of .040 in. is about the lowest permissible with a rotor of normal weight. Any reduction below this figure increases the risk of premature failure to a most dangerous extent, although the very precise running obtainable with a new sharp pivot at very low loads might appear to offer an inducement in this direction, but it must be remembered that the life of a pivot of small radius can only be very limited.

The ball bearing, with its ample bearing area and lower stresses, provides a very good compromise of all the requirements, and it excels particularly in the long life which it gives both under normal conditions and conditions rendered adverse by excessive overloads and the intermittent peak loads which are occasioned by the switching-on of certain domestic appliances, especially thermostatically controlled apparatus such as water heaters.

Reference to Fig. 1a and 1b will assist in clarifying several points regarding the ball bearings which are not as generally understood as they might be. The first is, that while the radius of the ball is .03125 in., the radius of the jewel cups in which it operates is .0465 in. The ball is therefore free to rotate and roll round in a small orbit at the centre of the jewel cup. The points of contact between the ball and the jewels are thus constantly changing, giving the effect of an infinite number of pivot points coming into action consecutively.

Secondly, since the movement of the ball is largely a rolling movement and the load is not permanently concentrated at one particular point, the effective areas of ball and jewel surfaces available for duty are considerably larger than exist in the pivot bearing. It must be conceded that in the case of the pivot bearing the actual area of jewel which is available for carrying the load is but a few thousandths of an inch in diameter approximately at the centre of the jewel.

The choice between ball bearing and pivot bearing will be decided by a number of considerations. If it is desired to extend the period between successive tests during service to the maximum time permitted by other circumstances, notwithstanding the fact that the meter may have periods of sustained unscheduled overload, then the ball bearing deserves the most careful consideration. The total costs now incurred in changing meters on premises will be an important consideration.

The pivot bearing will probably be called for where the period between tests is on a shorter time schedule and where it is felt that the risks of damage during transit between the test room and the consumers' premises are remote. The cost of bearing replacements will be in favour of the ball bearing as it is a very rare occurrence for any damage to be sustained either by the ball or jewels.

There is therefore no expected loss in revenue which might result from a meter running in service for several years with a damaged bearing.

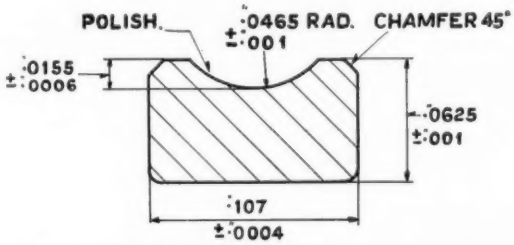


Fig. 4.—Dimensions of Synthetic Sapphire for Meter Bearings.

The costs of replacements of jewels and pivots in the pivot type will, of course, be higher, and these costs form a factor which cannot readily be estimated in advance, neither can the loss in revenue resulting from the continued use of a damaged bearing.

The manufacture of the components of the ball bearing is not without interest. The first cost is higher on account of the use of two jewels per bearing, but as far as the meter engineer is concerned he need not anticipate any cost on bearing renewals or repairs during the life of the meter.

There is no doubt that a badly made ball bearing for any piece of mechanism may be no better than a plain bearing correctly produced; in fact, it may quite conceivably be worse. The same principle applies to the manufacture of the ball bearing for meters.

Fig. 5.—Microscope with Jewel Inspection Attachment.

It is appreciated certain meter engineers have hesitated to adopt the ball-bearing type meter owing to disappointing experiences with earlier types produced in this Country. The successful manufacture of the ball bearings calls for special technique and experience, and it is noteworthy that the Company has had in use for several years the finest possible plant specifically designed and operated for the sole purpose of producing the double-jewel bearing. The microscope jigs and fixtures employed in the inspection of the component parts are also special developments to ensure the perfection of every part before assembly.

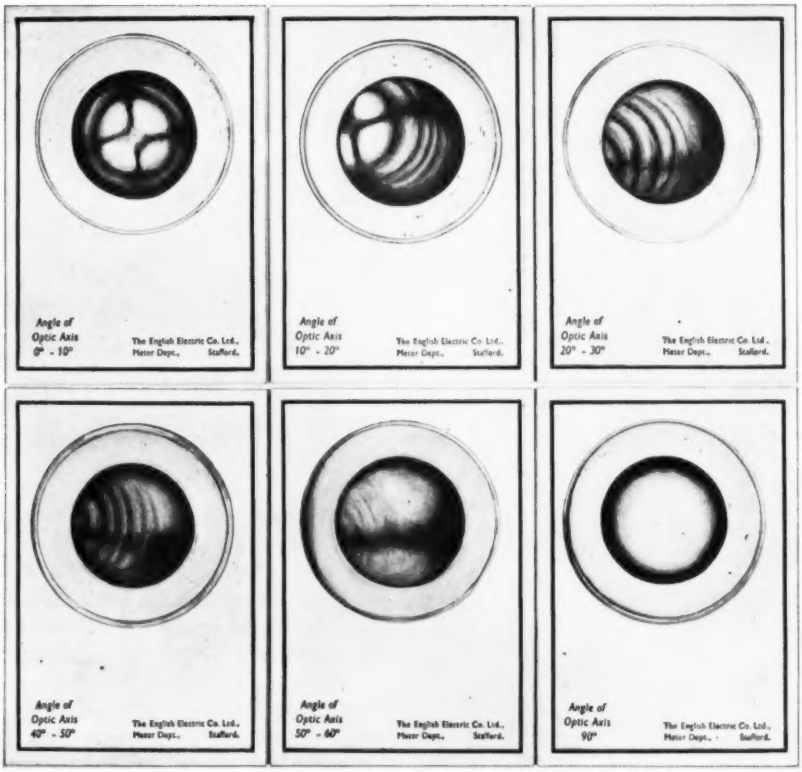
Given first-class components, correct manufacture and careful testing before assembly, the bearing has an indefinitely long life. All materials and components employed in the bearing are of the finest quality obtainable. Each of the two jewels is of the highest quality synthetic sapphire, which is purchased to a very stringent specification as regards dimensions, finish and material.

At a later date it is proposed to give some interesting information about the manufacture of meter jewels, but for the present only Fig. 4 is reproduced, which illustrates the dimensioned drawing of the jewel to indicate the small tolerances permissible on dimensions for jewels supplied to the Company. These are specified in order to ensure absolute interchangeability of all bearings and an identical performance from each.

The jewels are carefully gauged for compliance with the dimensional requirements and inspected under binocular microscopes at a magnification of 60 diameters for perfection of finish. Special microscope attachments are used for rotating and rocking the jewels under the objective lenses so that every portion of the bearing surface can be very closely scrutinised. Fig. 5 shows the apparatus used for this purpose.

Research within recent years has shown that the life of a jewel under given conditions is related to the angle between the axis of the shaft and the optic axis of the jewel. An angle of 90 deg. between the two gives the longest jewel life.

All the jewels are therefore purchased with a guaranteed optic angle of 80/90 deg., and a specially built polarised microscope is available in the Company's Stafford Meter Factory by means of which this feature can be checked readily and accurately. The jewel is examined in polarised light and the form and colours of the image observed are compared with a standard coloured chart representing the true image of jewels of known optic angle. Fig. 6 is a reproduction of a


Angle of Optic Axis 0° - 10°
The English Electric Co. Ltd., Meter Dept., Stafford.
Angle of Optic Axis 10° - 20°
The English Electric Co. Ltd., Meter Dept., Stafford.
Angle of Optic Axis 20° - 30°
The English Electric Co. Ltd., Meter Dept., Stafford.
Angle of Optic Axis 40° - 50°
The English Electric Co. Ltd., Meter Dept., Stafford.
Angle of Optic Axis 50° - 60°
The English Electric Co. Ltd., Meter Dept., Stafford.
Angle of Optic Axis 90°
The English Electric Co. Ltd., Meter Dept., Stafford.

METER JEWELS.

Fig. 6.—Form of Image produced in polarised light. Various optic angles from 0° to 90°.

photograph of the chart showing the form of the dark interference lines for jewels of various known optic angles. The dark lines are surrounded by spectrum colours not visible in the reproduction.

The steel balls are purchased to a very stringent specification covering material, finish and size. The usual guarantee on dimensions is one-tenth of one-thousandth of an inch, but the Company's experience shows that the majority of the balls do not differ from the nominal dimension by more than one-half of the permissible tolerance.

All the steel balls are individually inspected with very great care to eliminate those which do not come up to the high standard of excellence demanded. To carry out this operation with the required thoroughness another special microscope attachment is used, by means of which the ball is rolled over steadily in such a way that every portion of its surface is brought into sharp focus under the wide-field objective lenses. Fig. 7 shows the apparatus for use in the examination of the $\frac{1}{16}$ in. standard steel ball.

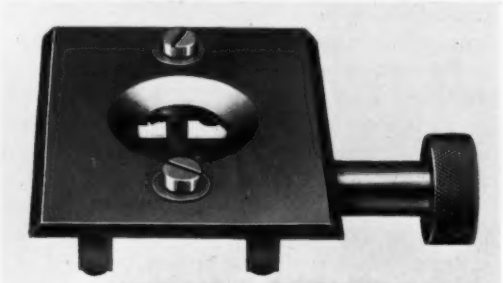


Fig. 7.—Microscope attachment for the examination of Steel Balls.

The Company for many years has been carrying out representative tests on a range of types of meter bearings and micro photographs are taken periodically to record the state of the component parts. A typical set of micro photographs are reproduced in Fig. 8.

Fig. 8(a). Synthetic sapphire meter jewel before use.

Fig. 8(b). Natural sapphire jewel from a ball bearing meter rotor which has completed 284 millions of revolutions.

Fig. 8(c). Synthetic sapphire jewel from ball bearing meter rotor after 207 millions of revolutions.

Fig. 8(d). Jewel from pivot meter damaged by excessive shock.

Fig. 8(e). Jewel from pivot meter. Completely shattered by excessive shock.

Fig. 8(f). Jewel from pivot meter showing signs of wear.

The photographs reproduced are approximately ten times actual size, but it should be understood that this comparatively low magnification is used only to obtain some indication of the general soundness of the jewel across its entire area. An enlargement to give a picture sixty or one hundred times normal size can readily be obtained in order to record any doubtful region in greater detail. For examination at magnifications of four hundred, a metallurgical micro camera is used either visually or to produce plates, but naturally the actual jewel area covered by such a photograph is quite small.

Figs. 8(b) and 8(c) show both the natural jewel and the synthetic jewel to be unimpaired after 284 millions and 207 millions of revolutions respectively.

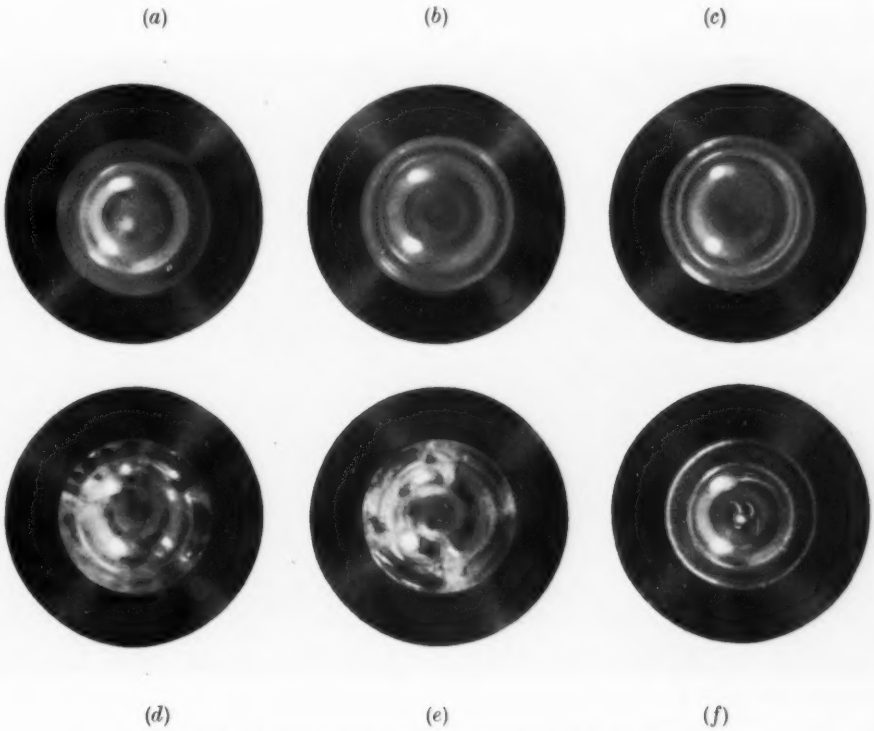


Fig. 8.—Enlarged photographic reproductions of Meter Jewels.

Until recent years the natural jewel was the only one used in meter bearings, but the synthetic sapphire is now in general use. Probably one of the most important advantages of the synthetic jewel is that the position of the optic axis with respect to the line of the meter shaft can be comparatively easily controlled in manufacture, as several hundred meter jewels are produced from a single " boule " or parent crystal of known optic axis. The natural jewel is produced from a comparatively small natural stone often rather irregular in shape, and the optic axis of the finished bearing jewel could not be guaranteed commercially.

It is hoped that this article will assist meter engineers in making a choice between ball bearing and pivot bearing type meters and will have explained a few of the problems associated with the most highly stressed bearing known to engineering—the watthourmeter lower bearing.

Methods and Economics of Power Factor Improvement.

In alternating current engineering the ratio of the actual power, as measured by wattmeter, to the apparent power, as measured by voltmeter and ammeter, is known as the Power Factor. This may be expressed :—

$$\frac{\text{Actual power}}{\text{Apparent power}} = \frac{\text{Kilowatts}}{\text{Kilovoltamperes}} = \frac{\text{kW.}}{\text{kVA.}}$$

= Power factor.

The apparent power can never be less than the actual power, and is usually more. If the two are equal the ratio $\frac{\text{kW.}}{\text{kVA.}} = 1.0$, and we say then that the power factor is unity. This can only apply when the load contains pure resistance without any reactance whatever. In all alternating current apparatus, or machinery, where a magnetic field has to be created, i.e., in motors, transformers, and all coil-wound apparatus, reactance is introduced. To a smaller extent even the simplest circuits or straight conductors set up a magnetic field, and this also constitutes reactance. In long overhead distribution systems such reactance may be appreciable.

The relationship between the apparent power and actual power is usually expressed in the form of vector diagrams. The cosine of the angle of displacement between the two power measurements is the power factor, i.e., in Fig. 1a, Cos $\phi = \frac{\text{kW.}}{\text{kVA.}}$ = Power Factor.

This relationship is sometimes likened to a truck on rails, or barge on a canal, where the

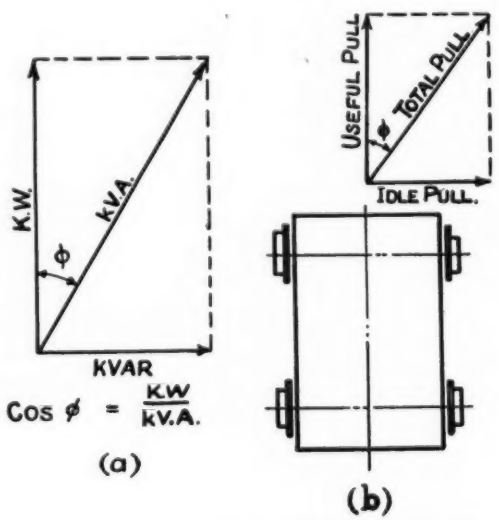


Fig. 1(a).—Vector diagram illustrating relationship between apparent and actual Power, whilst Fig. 1(b) illustrates a mechanical analogy.

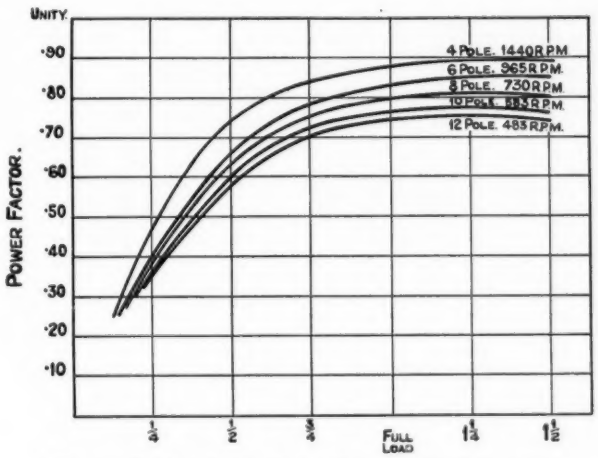


Fig. 2.—Typical Power Factor Curves of 20 H.P. 50-cycle Slipring Induction Motor.

pull is not directly in the line of motion. According to the usual force diagrams of mechanics, this "out of line" pull may be split up into two components; one in the line of motion being the useful effort, and another at right angles to the line of motion which is the side pull, or idle pull, because it does nothing whatever towards the motion of the vehicle. In the foregoing mechanical analogy, illustrated in Fig. 1b, the side pull is wasted energy, whereas in the electrical equivalent the sideways component represents true energy which at one time is taken from the supply to build up the magnetic field, but during the next quarter cycle is returned into the system from the decay of the magnetic field. The sum total of energy in this right angle, or quadrature, component is therefore zero, and is often termed "wattless." In this article we will call it kilovoltamperes reactive, or kVAR. and kVA. $= \sqrt{kW.^2 + kVAR^2}$.

In most industrial applications low power factor is mainly caused by induction motors, but of recent years the spread of A.C. electric arc welding and certain applications of electric furnaces has tended towards low power factor, since the stability of many such applications depends upon the deliberate introduction of reactance. Discharge lighting is another contributory cause, as the special transformers involved incorporate considerable reactance.

Fig. 2 gives some typical curves of power factor for induction motors of various speeds. It will at once be noticed that slow-speed motors have a lower power factor than the equivalent motors of higher speed, and also that the power factor becomes rapidly worse at reduced loads.

Low power factor means higher current, and all cables, transformers, switchgear and any current carrying apparatus must be made larger and more expensive in consequence. A power station designed for a mean power factor of 0.85 would only give 80 per cent. of its output at 0.70 power factor. As the capital cost of generation and distribution forms a large proportion of the cost of electric power, these economic disadvantages of low power factor are of great importance. In addition to this, there is the serious effect of poorer voltage regulation at lower power factor. Fig. 3 shows the voltage reduction on full load current at different power factors for a system having a combined reactance of 12 per cent. for transformers and feeders.

Methods of Power Factor Improvement.

(*a*) *Re-arrangement of Motors.*—Before considering the purchase of power factor correcting apparatus it is always advisable to investigate the

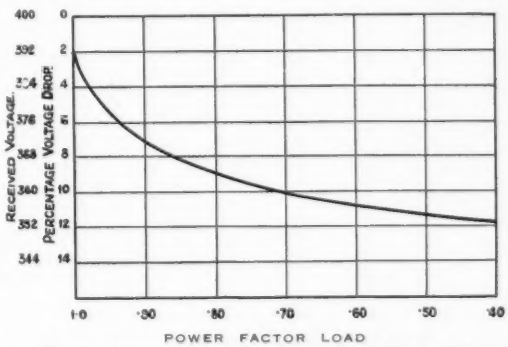


Fig. 3.—Curve showing the effect of Load Power Factor on received voltage for a Combined Transformer and Distribution Resistance 2%; Reactance 12%; Declared voltage 400.

loading and power factor of any existing motors during the maximum sustained load, taking into account any peak loads which the motors may have to withstand. Fig. 2 gives some indication of the improvement which may be attained by replacing overpowered motors with others which will be loaded more according to their scheduled rating, or where the drive permits of replacing low-speed motors with those of higher speed. Occasionally, where group drives are installed, the diversity factor in the peak loads of various machines may be taken advantage of, and a smaller motor used. It is frequently possible to interchange some of the motors or regroup some of the drives so as to effect an appreciable improvement in the overall power factor.

(*b*) *Static Condensers.*—Static condensers of the paper and foil type, usually oil immersed, and built up in units to suit the desired voltage and current, are widely used to improve the power factor of existing installations. Such banks of condensers may be placed in the works substation or may be distributed about the works close to the motors with which they are associated, whichever is found more convenient and economical. If placed in the substation they will correct the power factor on the incoming supply, but not on the works distribution system. In addition, it will probably be necessary to incorporate some switching arrangement so as to adjust the capacity of the condensers to the particular load, otherwise a leading power factor may be introduced and unwanted voltage rise may result. If the condensers are placed at the motor load they can be switched with the motor and the distribution cables will be relieved of current, but the installation will probably be more costly.

(*c*) *Capacitor Motors.*—The Company's three-phase capacitor motor consists of the usual form of squirrel cage or slipring induction motor, but has a condenser permanently connected across the stator phases with special control gear to give the correct starting sequence.

It is necessary to have the condensers manufactured to a suitable specification for such motors, as the design of the condenser must take into account the possibility of the motor, when disconnected from the supply, behaving as a self-excited induction generator and building up an undesirable voltage.

A very useful characteristic of these capacitor motors is that when designed for a combined power factor of about 0.98 lagging at full load, the power factor is almost constant down to quite low loads. Fig. 4 shows a slipring capacitor motor class AGS with its associated condenser.

(*d*) *Synchronous Motors and Synchronous Condensers.*—Salient pole synchronous motors may be used where the starting torque is small, say, not exceeding 25 per cent. of full-load torque. Damping windings are provided in the pole faces to provide starting torque and the motors are usually started on reduced voltage by means of an auto-transformer so as to limit the current taken from the line to about twice full-load current. Such motors are suitable for a continuously running load which starts up light, as, for instance, the driving of motor generator sets, large ventilating fans which do not have too

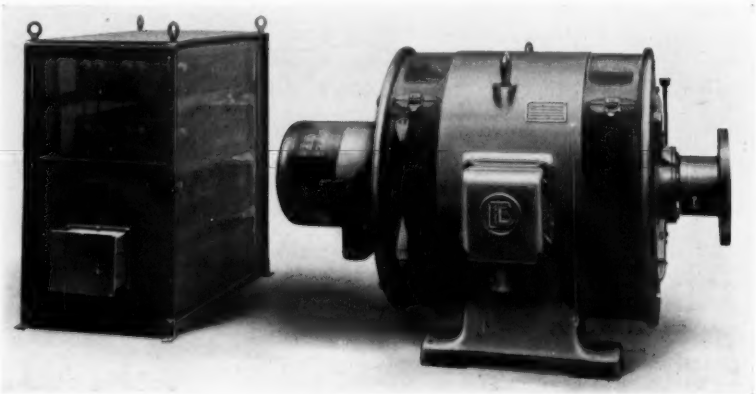


Fig. 4.—"English Electric" 125 H.P. 325 R.P.M. Class AGS. Slipring Capacitor Motor with Condenser.

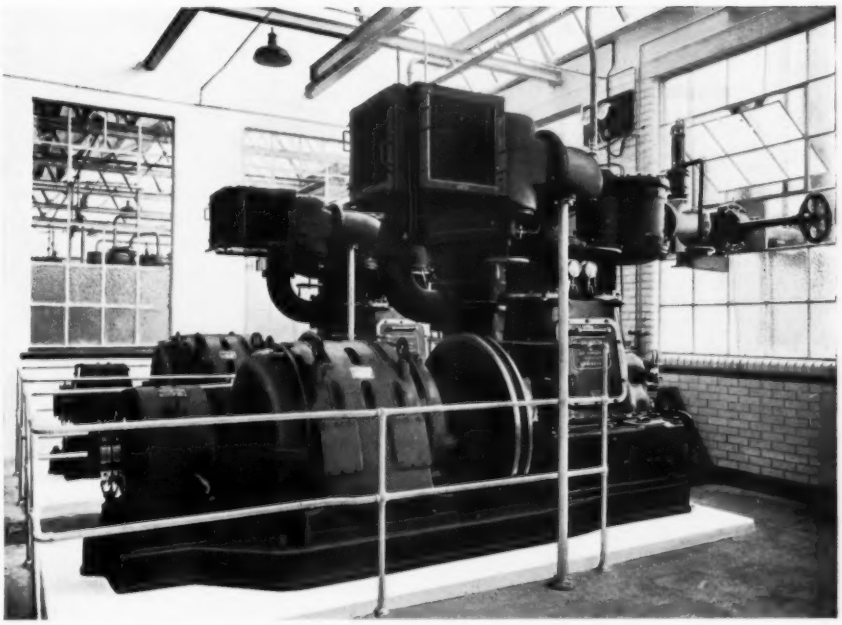


Fig. 5.—Two "English Electric" 270 H.P. Synchronous Induction Motors Class LTS. driving Air Compressors in a Glass Works.

heavy an impeller, some compressors which may be started with an unloading valve, and drives where the load may be taken up by means of a clutch. Salient pole synchronous motors are very efficient and may be run quite economically at leading power factors so as to form a correcting unit for other lagging power factor loads. Although it is usually more economical to combine power factor correction with a driven load, it is sometimes advantageous to instal synchronous running machines to run idly and merely supply leading wattless current for power factor correction. It will be seen that under such circumstances they are the equivalent of the static condensers previously mentioned, and when run idle in this manner they are known as synchronous condensers. The choice is mainly economic and depends on the cost per kVAR available for correction.

(e) *Synchronous Induction Motors.*—Where the starting load is too great for the salient pole type of synchronous motor, one of the alternative forms which start as induction motors may be employed. Starting methods and characteristics are similar to those of slipring induction motors, but when up to speed the D.C. excitation pulls

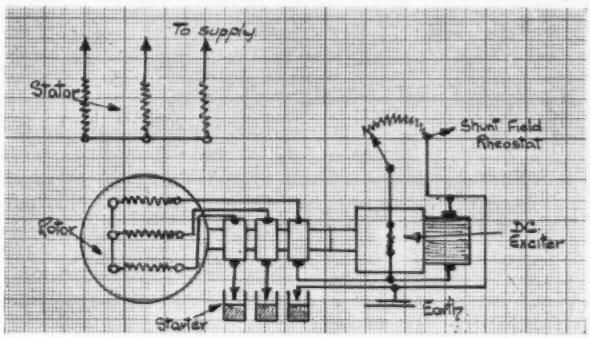


Fig. 6.—Diagram of connections for Synchronous Induction Motor—Class LTS.

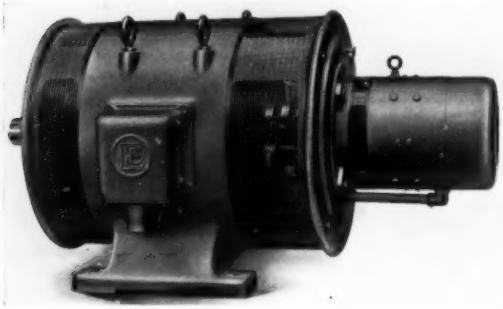


Fig. 7.—"English Electric" Class AGAS. Synchronous Induction Motor.

the rotor into step as a synchronous motor. Various arrangements are made according to h.p. of motor and service requirements, as follows:

(i) The class LTS. motor has the exciter permanently connected in the rotor circuit and automatically pulls into step without any special changeover or synchronising switches. This is suitable for small and medium size motors. Fig. 5 shows one of these motors driving an air compressor, and Fig. 6 gives the diagram of connections. Fig. 7 shows a smaller unit class AGAS. machine with a flange mounted overhung exciter.

(ii) For large outputs it is often desirable to use the class LAS. machine to obtain more suitable exciter characteristics. Fig. 8 illustrates one example, and Fig. 9 shows the diagram of connections.

(iii) A further development, mainly for the purpose of improved efficiency, is the wound rotor salient-pole class GLS. machine, which combines the high starting torque characteristics of the slipring motor with the other features of the salient pole synchronous motor.

(*f*) *Commutator Motors.*—Practically all A.C. commutator motors can be designed to operate at very high power factors and thus improve the overall power factor on an installation, whilst many can be economically designed to work at a leading power factor, which enhances their value as corrective devices. They give high starting torque with reasonable current from the line, and certain types are suitable for variable speed drives. The "English Electric" "Kosfi" motor is a typical example of the compensated induction motor and is illustrated in Fig. 10, whilst Fig. 11 shows the diagram of connections and current locus diagram. In this motor the supply is led to sliprings on the rotor and the starting resistance is in series with the secondary winding which is wound on the stator. In the same rotor slots as the primary winding is a special winding connected to the commutator. A voltage is produced by transformer action in this special winding and the frequency is converted by commutation, so that it can be fed into the secondary winding to provide the necessary kVAR. for magnetising.

(*g*) *Phase Advancers.*—Phase advancers are A.C. commutator machines for providing magnetising current without doing any mechanical work. They may be said to bear the same relation to A.C. commutator motors that synchronous condensers bear to synchronous motors. There is this great difference, however, that the actual

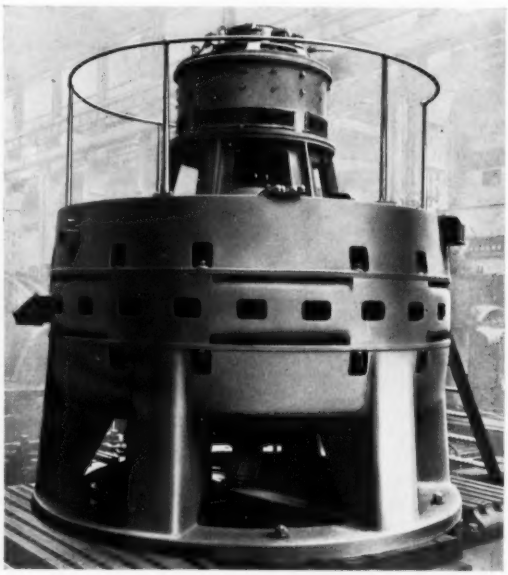


Fig. 8.—"English Electric" Class LAS. vertical-spindle type Synchronous Induction Motor 1320 H.P., 250 R.P.M.

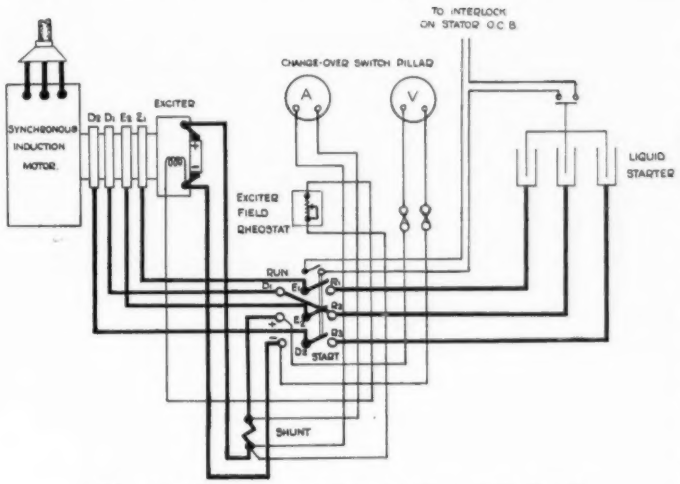


Fig. 9.—Diagram of connections for Class LAS. Machine.

kVAR. output from the phase advancer is effective in producing $\frac{100}{\text{slip}\%}$ times this amount of correction in the stator. This results in small output, highly efficient means of power factor correction and consequently small cost per effective kVAR. Phase advancers are connected in the rotor circuit of slipring induction motors and may be driven by the main motor or at any convenient speed by a small motor just large enough to supply the power represented by the phase advancer losses. Fig. 12 shows an "English Electric" phase advancer with its driving motor, which has been supplied for use with a 400 h.p. motor at a brick works.

Economics of Power Factor Improvement.

It has been shown earlier in this article that low power factor increases the size of all current-carrying parts which are subjected to such conditions, and may actually limit power station output. These considerations are the main items for those who generate their own power. It is significant that for continuous process plants, i.e., 24 hours per day, it is found most economical to install plant which works at about unity overall power factor. The additional capital cost of corrective plant is more than counterbalanced by the smaller capital cost of generating plant and distribution system, together with reduced losses in operation. On the other hand, and from another aspect, there was an instance of a colliery with a fully loaded 3,000 kVA. turbo-alternator which added a 700 h.p. air compressor driven by a synchronous induction motor running at 0.85 leading power factor without increasing the power plant capacity.

Where consumers buy power from an outside source on a flat rate per unit with or without a maximum kW. demand charge, it does not usually pay to install power factor correcting motors or apparatus unless there is also a penalty or rebate on power factor. An increasing number of supply authorities, however, are finding it necessary to

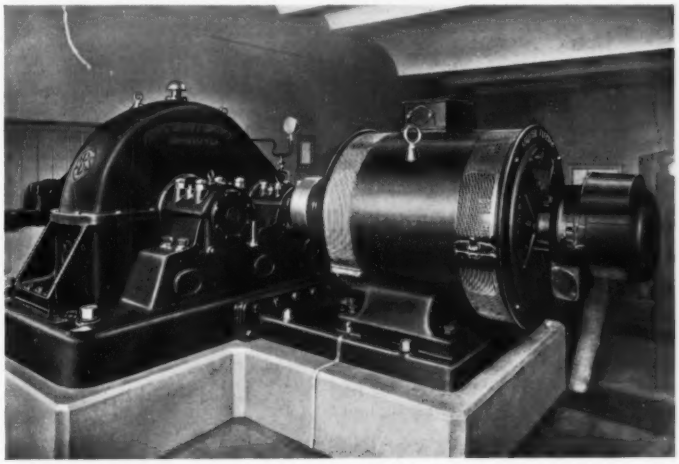


Fig. 10.—"English Electric" 300 H.P. "Kosfi" Motor in a Brick Works.

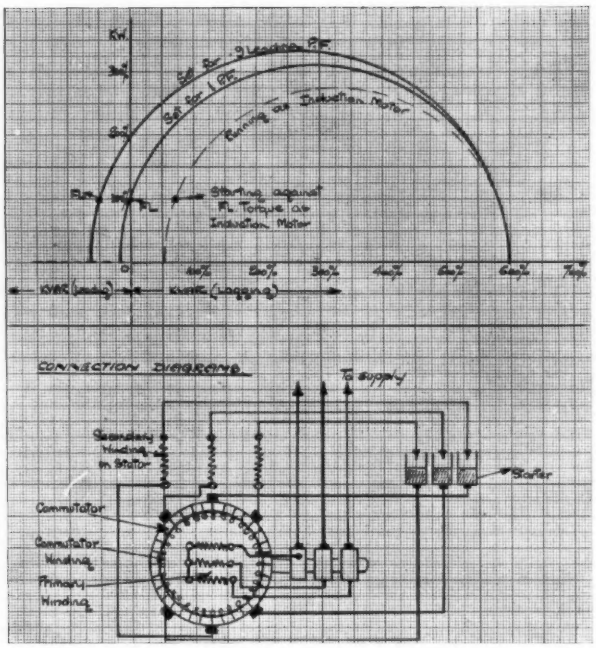


Fig. 11.—Diagram of connections and current locus Diagram for a "Kosfi" Motor.

make such charges or offer rebates owing to the power factor conditions obtaining on their systems. It is an easy matter to compare the capitalised value of the possible saving in power bills with the cost of corrective methods.

Those consumers who purchase power at a definite rate per unit plus a maximum demand charge based on kVA. are automatically penalised for low power factor, and there is an economic maximum up to which it will pay for improvements to be made. It can be shown by practical examples and by mathematical analysis that for a wide range of conditions this maximum, beyond which it does not pay to improve the power factor, is about 0.98. Omitting the mathematical treatment, let us examine a few typical cases.

Example 1.—Let us assume a works which takes a load of 500 kW. at 0.80 power factor, i.e., 625 kVA. There is a fixed charge per unit plus an annual charge £5 10s. 0d. per kVA. maximum demand. Also, it is assumed that the cost of power factor corrective apparatus will be £3 10s. 0d. per kVAR. and charge interest + depreciation at 12½ per cent.

Correction will be to 0.98 power factor.

Existing load has reactive component of	375	kVAR.
Corrected load has reactive component of	102	,,
Apparatus connected must be for	273	,,

Cost of power factor correcting apparatus
273 × £3 10s. 0d. = £955

Maximum demand reduced from 625 kVA. to 510 kVA.

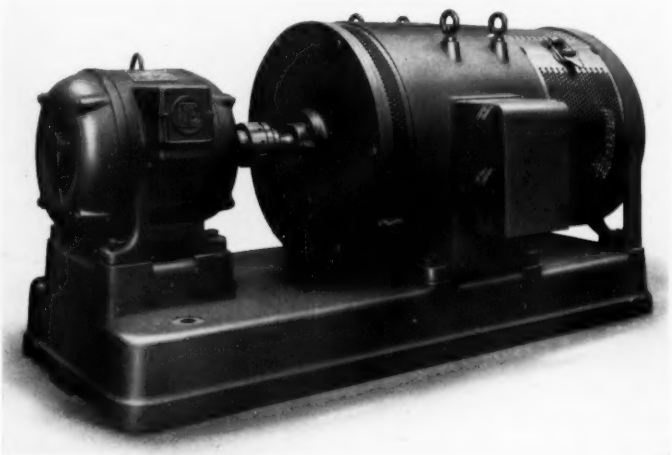


Fig. 12.—"English Electric" Phase Advancer and Driving Motor.

Annual charge on 625 kVA. at £5 10s. 0d.	=	£3,440
Annual charge on 510 kVA. at £5 10s. 0d.	=	£2,800
Difference in power bill	=	£640
Less 12½ per cent. on capital expenditure of £960	=	£120
Net annual saving	=	£520

To correct to 0.96 power factor would have required a capital expenditure of £800, but the net annual saving would only be £470. On the other hand, to correct to unity would have required a capital expenditure of £1,310, and the net annual saving would be reduced to £514.

Example 2.—In this instance let us assume a load of 1,200 kW. at 0.76 power factor = 1,580 kVA. with a reactive component of 1,030 kVAR. Also let us assume a maximum demand charge of £4 5s. 0d. per annum, and that the largest unit of power is a 600 h.p. compressor motor taking 480 kW. at 0.80 power factor. This motor is a very suitable application for a synchronous induction type motor, so let us consider replacing the existing induction motor with one of the synchronous types working at 0.85 leading power factor. By this means the 360 kVAR. of the existing motor will be eliminated and a further 300 kVAR. supplied for correction, making a difference of 660 kVAR. The new conditions will, therefore, take 1,030 − 660 = 370 kVAR., and the combined power factor will be improved to 0.957 with a kVA. maximum demand of 1,250 instead of 1,580.

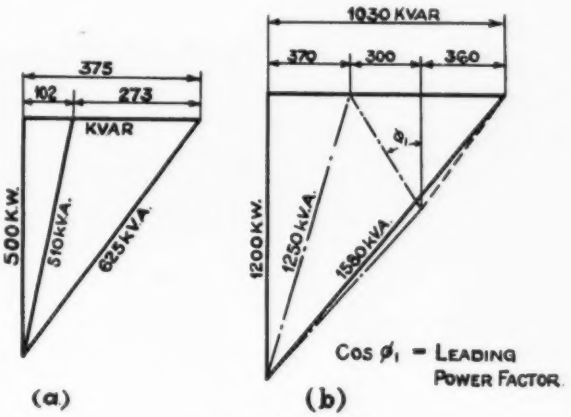
Maximum demand charge reduced 330 × £4 5s. 0d. ...	=	£1,400
Interest and depreciation on £1,600 capital cost of new motor, at 12½ per cent. ...	=	£200
Net annual saving ...	=	£1,200

It should be noted that this shows a very favourable result even when debited with the whole cost of the new motor with no allowance for the old one. The difference in cost between an induction motor and a synchronous induction motor of this size is less than £400, and as this makes a difference of 660 kVAR. the cost per kVAR. is under 12s., which is very favourable.

Calculation of Size of Corrective Devices.

The two examples worked out in the previous section, to show the financial saving, are depicted vectorially in Fig. 13 (*a*) and (*b*) respectively. It is at once apparent that loads at different power factors cannot be added in a simple arithmetical manner. The components kW. and kVAR. can each be added arithmetically and then recombined to find the new kVA. Vector diagrams merely do this in unit dimensions, and if drawn with care to a reasonably large scale, are sufficiently accurate for most practical purposes. Quantitative solution is, however, to be preferred and the Company have introduced a combined Slide Rule and Power Factor Calculator (Patent Application 30421/38) in the form of a 5 in. pocket slide rule, which makes the solution of such problems a simple matter.

A curve is reproduced in Fig. 14 which is also intended to assist in power factor calculations. In this curve Tan ϕ is plotted as ordinates against Cos ϕ and so represents the kVAR. required per kW. of load at any power factor over the range



Figs. 13(a) and 13(b).

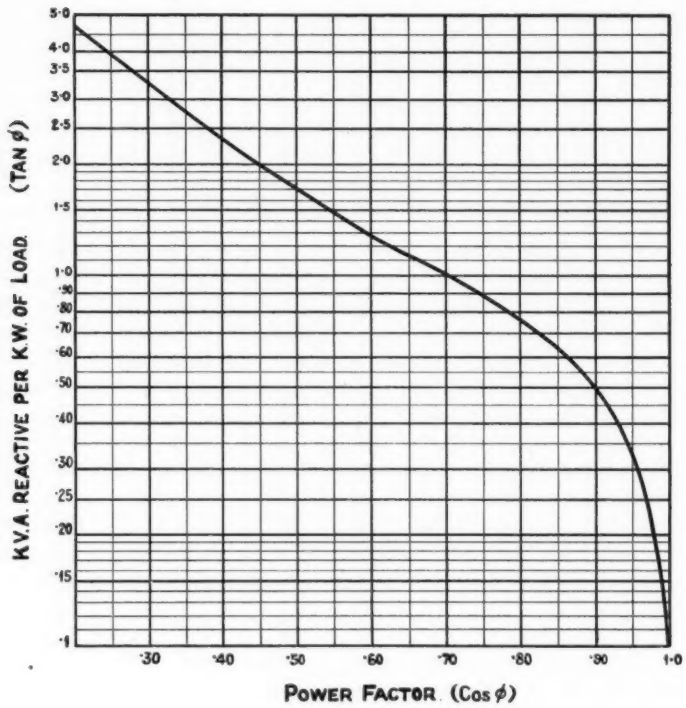


Fig. 14.

of the curve. In Example 1 (page 178) one can read from the curve :—

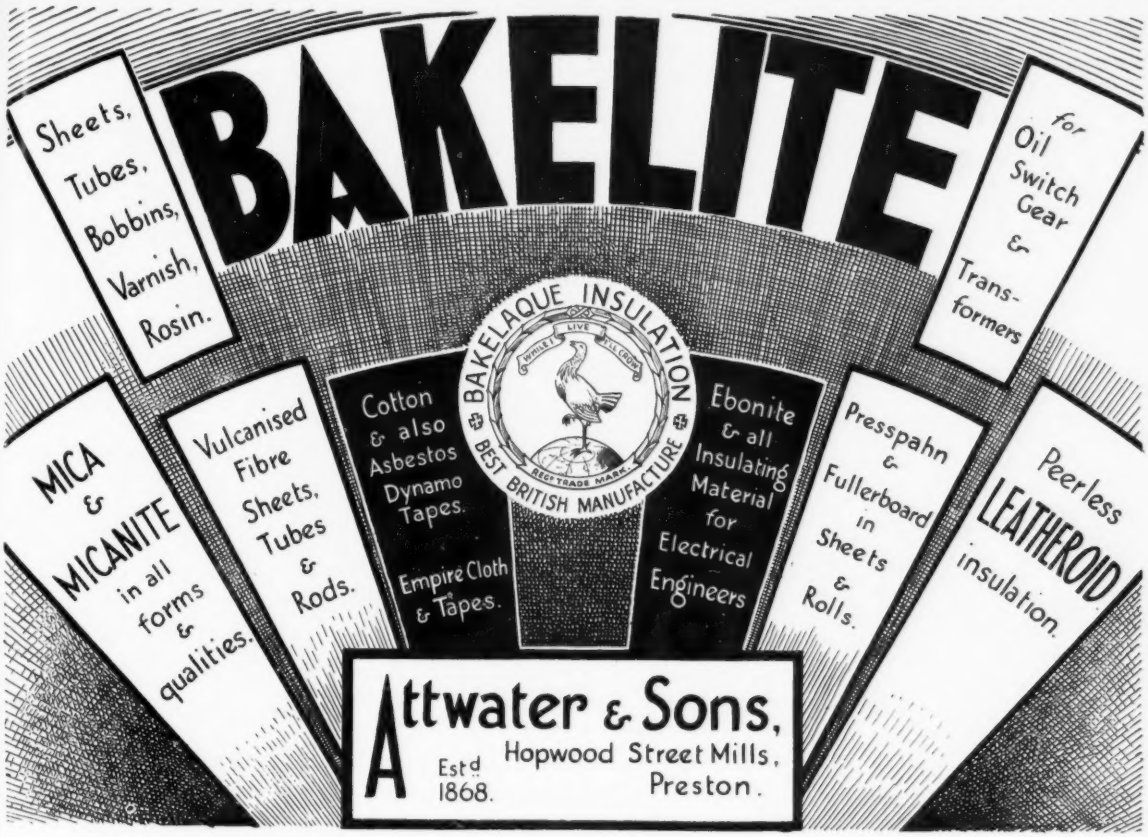
kVAR. per unit at 0.8 power factor = .75
,, ,, ,, ,, 0.98 ,, ,, = .204

connected apparatus must be for 500 (.75 − .204) = 273 kVAR.

In Example 2 it is desired to find the resulting kVAR. and consequent power factor. From the curve one may read :—

kVAR. per unit at 0.76 power factor = .86
∴ kVAR. initially is 1,200 × .86 ... = 1,030
kVAR. per unit at 0.80 power factor = .75
,, ,, ,, ,, 0.85 ,, ,, = .62
∴ kVAR. correction = 480 (.75 + .62) = 660
Final kVAR. = 1,030 − 660 = 370

$$= \frac{370}{1{,}200} \text{ per unit} = .308$$

and one may then read from the curve that .308 corresponds to a power factor of 0.957, and the maximum demand is therefore $\frac{1{,}200}{.957} = 1{,}250$ kVA.

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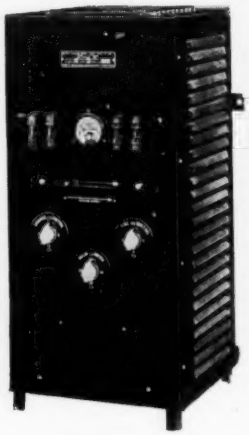

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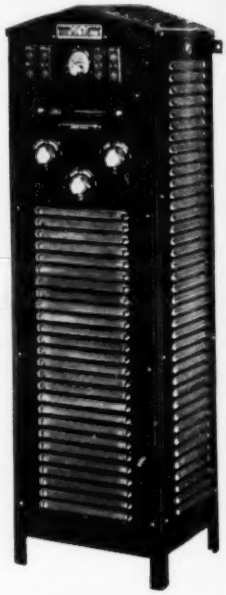

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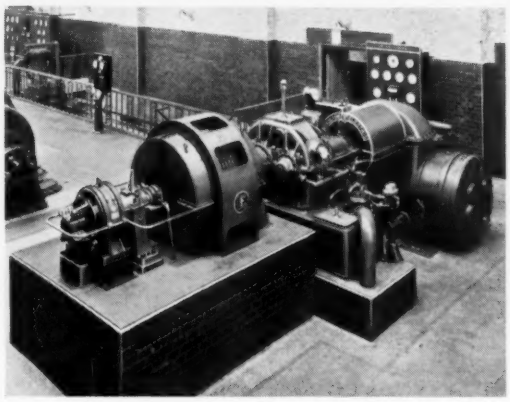

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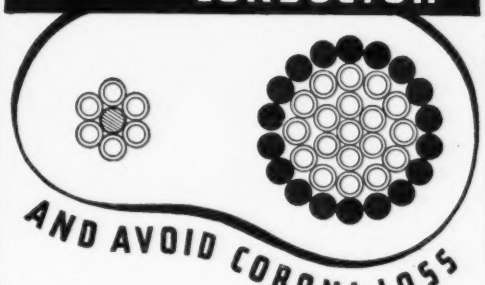

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Equivalent copper section, 0.3 sq. in.
Weight per 1000 ft. 1580 lbs.
Breaking load - 8.3 tons

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To avoid corona loss in E.H.T. work, the overall diameter of the conductor must exceed a minimum value, which depends on the conditions. Bolton Cellular Conductors achieve this result without any increase in weight. Their principal feature is the substitution of hollow wires for a number of the solid wires of the ordinary stranded conductor.

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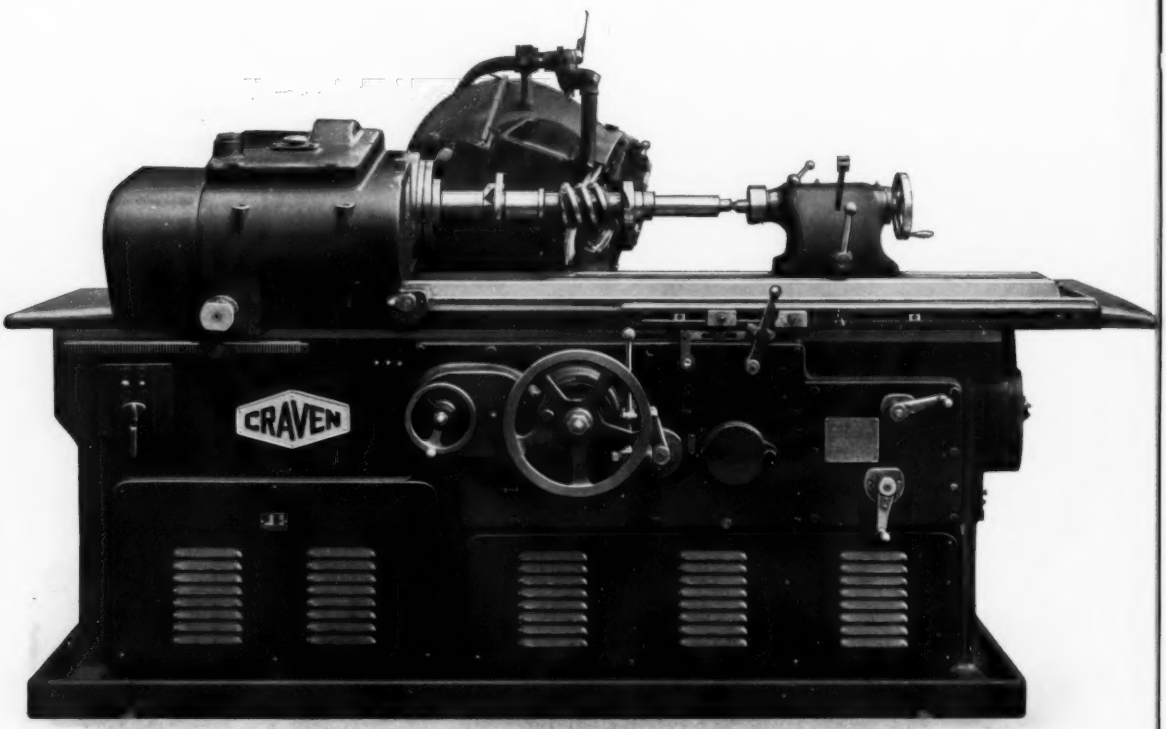

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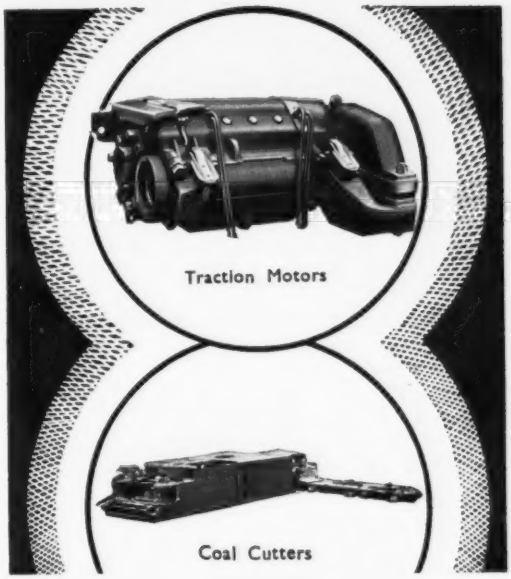

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